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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking University of Southampton as follows: The contractor will investigate two areas: (1) explore optically tuned fiber grating written in bi-refringent fiber; and (2) study photorefractive and relevant nonlinear characteristics of glasses with enhanced non-linearity.

In accordance with the specification, a fiber grating should be tuned within the range of 1 nanometer and dynamic rise-time shorter than 100 picosecond. The most straightforward way to achieve such a tuning ability is to use high intensity pulses in order to be above to change refractive index difference between core and cladding. In order to be able to do so one has to produce pulse intensities in order of 10^{11} W/cm^2. The main activity within the project was concentrated around development of a diode-pumped, reliable source of high intensity pulse and has successfully demonstrated optically-tuned fiber grating.

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Optically Tuned Fibre Gratings

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I. Introduction

In this report we present the results of our activity within the project.

In accordance with the specification a fibre grating should be tuned within the range of 1 nm and dynamic rise-time shorter than 100 ps. As it was stated in the preliminary report the most straightforward way to achieve such a tuning ability is to use high intensity pulses in order to be able to change refractive index difference between core and cladding. In order to be able to do so one has to produce pulse intensities in order of 10^{11} W/cm^2. Thus main activity within the project was concentrated around development of a diode-pumped, reliable source of high intensity pulses.

III. Experimental results

III.1 Master Source

Passively modelocked fibre lasers are most suitable sources of short optical pulses for laboratory applications because of their properties of simplicity, tunability and picosecond pulse generation. Passive modelocking of fibre lasers has been demonstrated in both ring and figure of eight configurations [1,2]. The energy quantization effect in the soliton regime of operation of these lasers leads to excellent stability of individual pulses but instabilities in the repetition rate make these devices unsuitable for many applications. In particular, for a reliable source of high intensity picosecond pulses one would need a repetition rate in order of 50 MHz with timing jitter between the pulses below 1 ps.

One solution to this problem is to operate the laser with just a single pulse in the cavity but this gives low repetition rates and low output powers. Several other techniques have been demonstrated including intra-cavity modulation [3], additional sub-cavities [4] and extra-cavity feedback [5] but these may be difficult to implement in a practical system.

Recently, self-stabilization of the repetition rate has been observed in a fibre ring laser. This occurs because acoustic waves generated in the fibre by electrostriction cause slow perturbations of the laser cavity which modulate and retime of the pulses. Using this technique sub-picosecond timing jitter has been achieved but the need for sensitive polarisation control still makes this device impractical.

Other passive modelocking techniques based on multi-quantum well (MQW) saturable absorbers have also been demonstrated in both linear and ring cavities and pulses as short as 1.2 ps have been reported [6]. These lasers are easy to self start but often do not produce transform limited pulses and do not quantize the pulse energy. Quantization of the pulses is desirable because it fixes the pulsewidth and intensity to values defined by the laser cavity, e.g. by the length of the loop mirror in a figure of eight laser. This means that variations in the pulse parameters at the output are minimized and are not affected by external factors such as pump power variations. The quantization effect also means that the number of pulses in the cavity is proportional to the power supplied to the amplifier and can be controlled by the changing the pump power.

A practical passively modelocked laser needs to be self-starting and capable of generating clean, uniform pulses at a stable repetition rate. In this letter we describe experiments on a new design of fibre laser cavity which achieves these aims by combining the ease of self starting of saturable absorber modelocked lasers with the soliton shaping

properties and intensity discrimination of a nonlinear amplifying loop mirror (NALM). The combined action of a semiconductor saturable absorber and a NALM form a hybrid saturable absorber which is able to suppress the spectral side-bands observed in soliton lasers and provide clean picosecond soliton pulses at the output. The presence of the semiconductor also provides a slow perturbation to the cavity which is able to provide self stabilization.

The configuration of the laser is shown in Fig. 1.

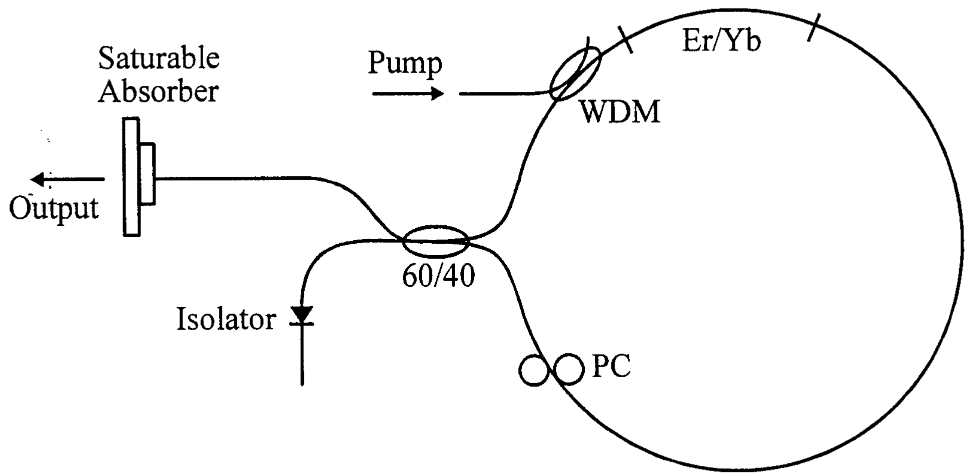

Fig.1 Configuration of laser cavity

A NALM is formed between the output ports of a 60/40 coupler and includes ~100 metres of standard telecom fibre, a polarisation controller and a 2 metre long Er/Yb co-doped fibre amplifier pumped by a miniature Nd:YAG source providing 200 mW of launched pump power at 1064 nm. An InGaAs/InP MQW saturable absorber and Bragg reflector stack is butted to the input port of the NALM. The MQW consists of 82 periods of 65 Å thick InP and 78 Å thick InGaAs. An isolator is spliced to the other port of the NALM to prevent feedback into the loop.

The laser has two regimes of operation. In the first regime, square pulses are generated at the fundamental cavity frequency of 1.8 MHz for almost any position of the polarisation controller. The duration of the pulses can be varied from ~10 ns down to ~500 ps by varying the pump power to the amplifier while the peak power of the pulses is fixed by the power required for switching in the NALM.

The second regime of operation is reached by adjusting the polarisation controller to set the correct phase bias in the NALM for soliton pulses to be generated. When the laser entered this regime of operation it was found that passive stabilization of the soliton repetition rate occurred with the repetition rate at harmonics of the fundamental frequency. Once the correct bias in the loop has been set the laser remains stable for several hours and after being switched off will self start in the passive harmonically modelocked regime. By using polarisation maintaining fibre in the loop it may be possible to fix the phase bias in the NALM and remove any need for polarisation control.

Output spectra for the soliton regime of operation taken at a repetition rate of 250 MHz are shown in Fig. 2.

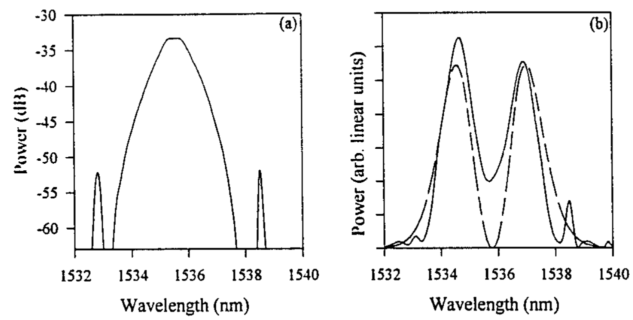

Fig.2 Spectral characteristics of the soliton laser

Fig. 2a shows a spectrum taken from the spare port on the WDM in the NALM. The spectral width is 1 nm indicating a pulsewidth of 2.5 ps. The spectrum also demonstrates 20 dB suppression of the spectral side-bands commonly seen in fibre soliton lasers. This is attributable to the combined intensity discrimination of both the NALM and the saturable absorber. In the NALM the low intensity non soliton component which gives rise to the side-bands is switched out of the laser. Any remaining non soliton radiation is then further suppressed by the action of the saturable absorber. Fig. 2b shows a spectrum taken from the spare port of the NALM. This clearly shows that the soliton part of the spectrum has been switched back into the laser by the NALM while the non-soliton radiation is rejected from the laser cavity.

The presence of the NALM in the cavity fixes the peak power of the pulses to give the correct nonlinear phase difference required for switching of the pulses. In the soliton regime of operation this also fixes the pulsewidth and quantizes the energy of the pulse which allows the pulse repetition rate to be easily tuned by adjusting the pump power to the amplifier. By varying the pump power launched into the amplifier from the mini-YAG we were able to tune the pulse repetition rate in the range ~100-400 MHz. To obtain higher repetition rates from the laser the mini-YAG was replaced by a high power YAG. In this configuration repetition rates of up to 1.5 GHz (>800th Harmonic) were observed. However fluctuations of ~20% in the pump power create instabilities in the repetition rate due to extra pulses being created or disappearing from the cavity because of the quantization effect. Stable operation at such high harmonic frequencies would require stabilization of the pump power to 1 part in 10^3 which is obviously a disadvantage for generating very high repetition rates from this laser. Shortening the cavity length and operating at lower harmonics would reduce this requirement but this will generate shorter pulses and require

higher pump powers. Fig. 3 shows excellent pulse train stability in harmonically mode-locked regime [7].

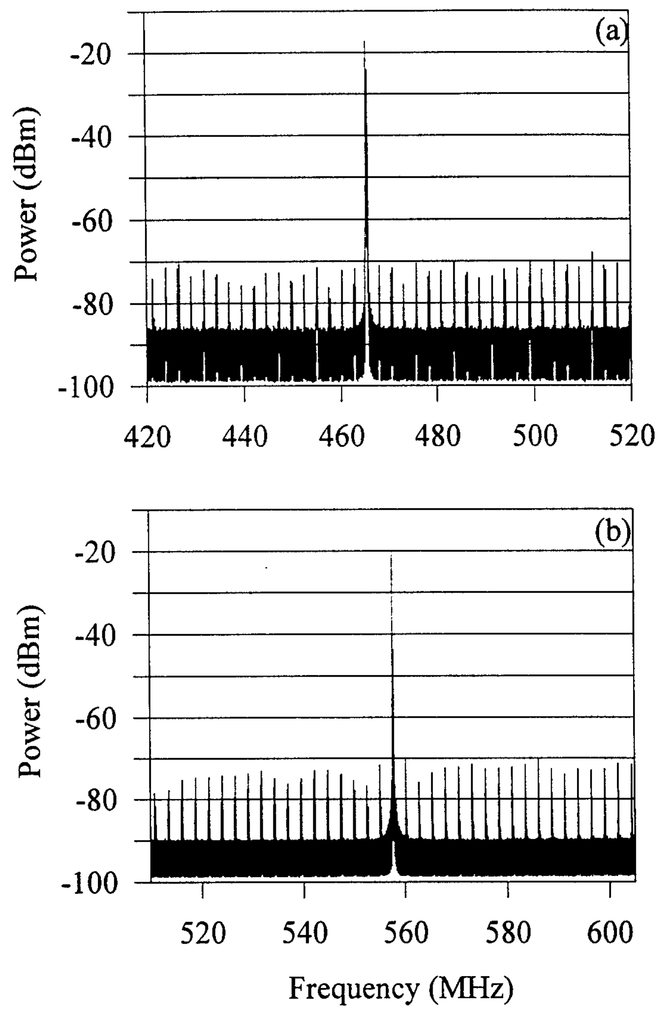

Fig.3 RF spectra of the soliton laser

III. 2 Chirped-pulse amplification scheme

In order to obtain high intensity pulses we have to amplify output from the soliton laser. However direct amplification of the output pulses can not be done due to limitations imposed by fibre nonlinearity. Indeed from a consideration that nonlinear phase shift should be less than π one can derive a simple relation

$$kn_2Iz < \pi$$

Typical amplifier length is about 4 m including WDM and couplers pigtails and effective area ~ 50 μm^2 and from the last relation one has $P_{max} < 300$ W.

In order to overcome this problem we adopted a so-called chirped pulse amplification technique. The idea is based on a pulse stretching prior amplification with subsequent pulse compression. Fig. 4 shows schematic representation of the experimental set-up.

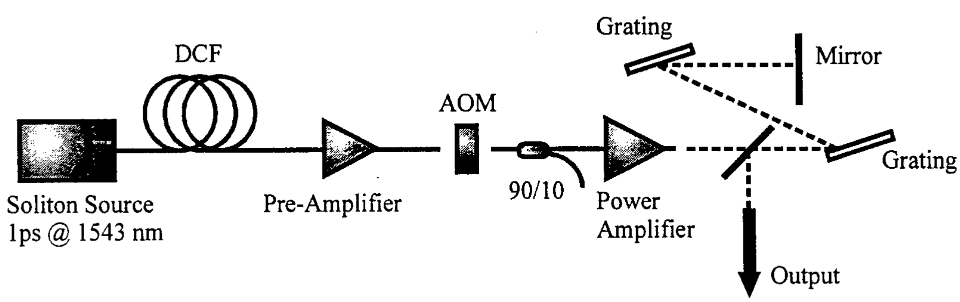

Fig.4 Experimental set-up for chirped pulse amplification

As a master source we use a soliton fibre laser with hybrid saturable absorber described in previous section. Pulses from the master source were launched into a dispersion-compensating fibre and stretched to 200 ps. Fig,5 shows pulse shape before and after DCF.

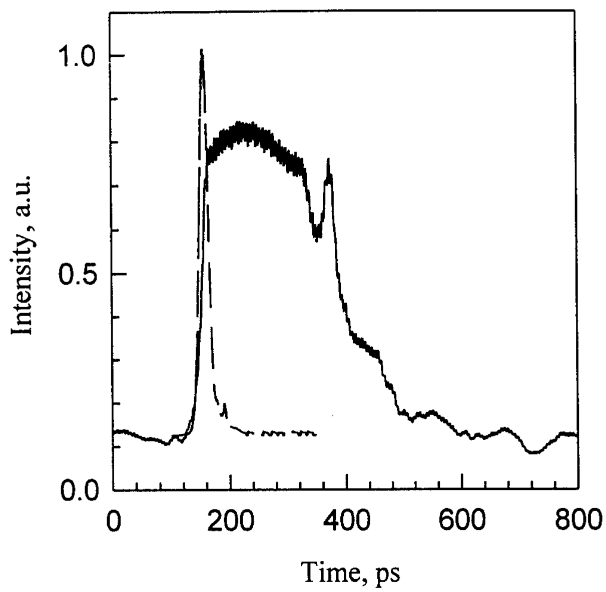

Fig.5 Pulse shape at the input (dashed) and output of the dispersion-compensating fibre

200 ps pulses then pass through a diode-pumped Er/Yb co-doped fibre amplifier, acousto-optic modulator and a power amplifier. Average power at the output of the power amplifier was 260 mW for 900 mW of pump power so that efficiency of the amplifier was about 30%.

The pulses then were compressed in a bulk grating compressor. The output power of the entire system was 70 mW and pulsewidth of the compressed pulses was 1.1 ps. Fig.6 shows autocorrelation trace at the output of the compressor. Maximum peak power of 40 kW was achieved at the AOM the repetition rate of 10 kHz [8].

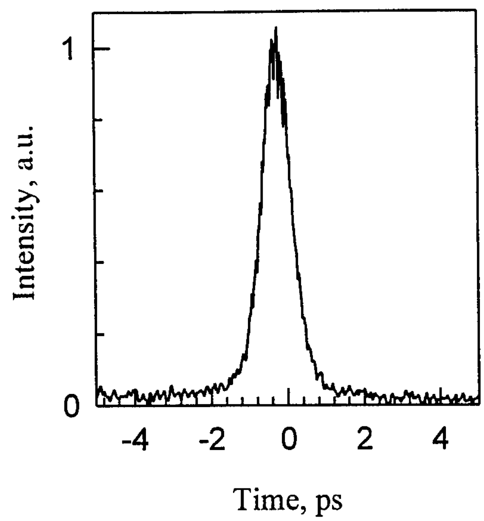

Fig.6 Autocorrelation trace at the output of the compressor

III.3 Experimental demonstration of optically-tuned fibre grating

Experimental set-up is shown in Fig. 7.

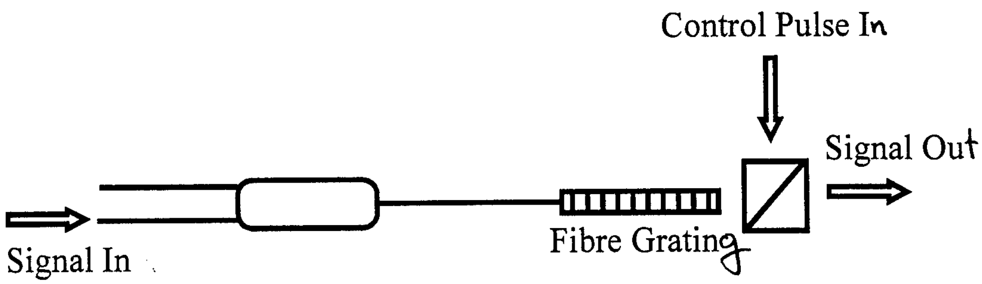

Fig.7 Experimental set-up of optically-tuned fibre grating

Note the tuning mechanism is based on change of grating refractive index due to Kerr effect and therefore it is possible to use control pulse with central wavelength outside of the grating bandwidth. So in our experiment we use control pulse with central wavelength of 1544 nm, while grating bandwidth was centred at 1550 nm.

As a signal we use an ASE source centred around 1550 nm. Note also that due to high intensity of control pulses we have to avoid the control pulse propagation through auxiliary fibres. That is why we use a bulk polarization beam splitter. The fibre grating length was 50 cm with centre wavelength at 1550 nm.

Fig.8 shows results of the experiment.

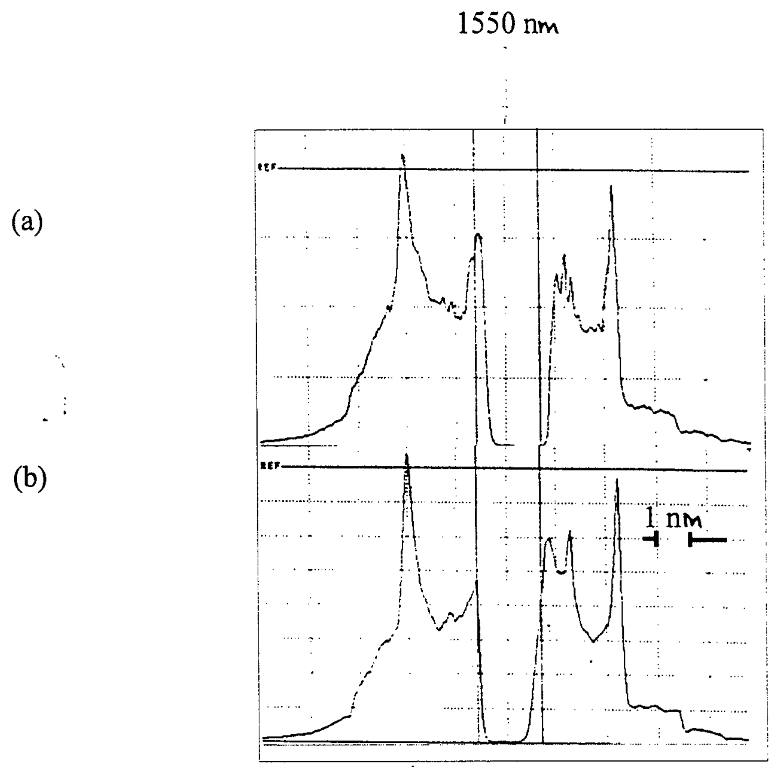

Fig.8 Transmitted spectra of fibre grating without (a) and with (b) control signal

From Fig.8 we can see that intensity-induced spectral shift is about 0.15 nm which in a good agreement with the theoretically predicted shift for the control peak power used.

VI. Conclusion

In conclusion, we have developed a diode pumped high peak power pulse source of picosecond pulses and successfully demonstrated optically-tuned fibre grating.

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